Active crustal extension and strain accumulation from GPS data in the Molise region (central-southern Apennines, Italy)

R. Giuliani[1], N. D'Agostino[2], E. D'Anastasio[2], M. Mattone[1], L. Bonci[3], S. Calcaterra[3], P. Gambino[3] and K. Merli[3]

[1] *Dipartimento della Protezione Civile, Ufficio Rischio Sismico, Roma, Italy*

[2] *Istituto Nazionale Geofisica e Vulcanologia, Roma, Italy*

[3] *Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici - Servizio Geologico d'Italia, Roma, Italy*

(Received: March 17, 2008; accepted: June 24, 2008)

ABSTRACT In this paper, we report new GPS measurements which indicate active NE-SW extension and strain accumulation in the Molise region (Apennines, Italy). The GPS observations were collected during campaigns on benchmarks of the dense IGM95 network (average distance 20 km), spanning a maximum observation interval of 13 years, and have been integrated with measurements from the available permanent GPS sites. Considering the differential motion of the GPS sites, located on the Tyrrhenian and Adriatic coasts, we can evaluate a 4-5 mm/yr extension accommodated across this part of the Apennines. The velocity field exhibits clusters of sites with homogeneous velocity vectors, outlining two main divergence areas, both characterized by the largest velocity gradients: one near Venafro and the other near Isernia where two primary active faults and several historical earthquakes have been documented. These results suggest that an active extension in this part of the Apennines can be currently distributed between the two faults systems associated with the largest earthquakes of this region.

1. Introduction

Strain accumulation on seismogenic structures provides the elastic energy which is then released during seismic events. The distribution of seismicity, together with the recognition of active faults, represent the main tools for evaluating the strain accumulation which could be potentially released in future earthquakes. On the other hand, estimates of surface strain accumulation detected with geodetic methods provide an independent piece of information for seismic hazard assessment, especially with the advent of the GPS technique. The development in the last decades of the use of GPS has allowed us to infer the active velocity field and strain rates, thus improving the knowledge concerning active fault behaviour, and constraining the local geodynamics.

The Apennines are characterized by an intense historical (Gruppo di Lavoro CPTI, 2004) and instrumental seismicity (Castello *et al*., 2006) and active NE-SW extension localized in a 30-50 km wide belt running along the crest of the mountain range. Previous works have shown that GPS measurements estimate the extension rate across the Apennines and contribute towards resolving the partitioning of deformation on the different seismogenic structures (D'Agostino *et al*., 2001; Serpelloni *et al*., 2005; Mantenuto *et al*., 2007; D'Agostino *et al.,* 2009). This is particularly important in the sectors of the Apennine belt, where large historical earthquakes are not associated to evident active tectonic structures, or to geological and morphological expressions recognized so far.

In 1994, the Italian Istituto Geografico Militare (IGM) carried out the IGM95 project aimed at the establishment of a national first order geodetic GPS network (Surace, 1997). The IGM95 network consists of 1236 sites over the whole Italian territory, at a mean separation of 20 km. This paper is concerned with the results of a series of campaign measurements, performed in 2001, 2003 and 2007 by the Dipartimento della Protezione Civile Nazionale (DPC), the Istituto Nazionale di Geofisica e Vulcanologia (INGV) and Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici (APAT) of a IGM95 sub-network made up of 20 stations in Molise and Campania regions. Episodic measurements have been combined with permanent GPS measurements from different networks. The velocity field and the crustal strains are considered so as to address the total extension rate accumulated in this sector of the Apennines and to evaluate how seismogenic structures accommodate strain accumulation.

2. Seismotectonic setting

The seismicity of the southern Apennines is concentrated in a axial 30-50 km wide belt located in the upper crust, being the seismogenic layer 12-15 km thick (Chiarabba *et al*., 2005a). The Molise region is a sector of the southern Apennine belt characterized by an intense seismicity (Gruppo di lavoro CPTI, 2004; Chiarabba *et al*., 2005a) (Fig. 1). Several high-energy earthquakes struck the Molise region with $M > 6.5$ in 346, 847, 1349, 1456, 1688 and 1805.

The structural setting of the area is a fold and thrust belt generated by the westward subduction of the Adriatic lithosphere (Patacca and Scandone, 1989). At present, the prevalent tectonic regime is a NE-SW extension due, according to some authors (Anderson and Jackson, 1987; Calais *et al*., 2002; D'Agostino *et al*., 2005), to the rotation of the Adriatic block (the foreland of the former subduction zone) relative to Eurasia around a pole of rotation in the western part of the Po Plain. This rotation fits with the styles of an active extension shown by earthquake focal mechanisms, geological and paleoseismological data and by geodetic observations. At a regional scale, the geodetic strain field for the southern Apennines, as inferred from the GPS re-occupation of the first order triangulation network over the past 130 years, is dominated by an extension perpendicular to the axis of the chain. The deformation is mainly concentrated in a 30-50 km wide belt with an extension rate of around 3 mm yr^{-1} (Hunstad *et al.,* 2003). According to Selvaggi (1998), the extension rate assessed from the summation of seismic moment tensors of recent and historical earthquakes located in the same axial Apennine area is around 2.0 mm yr^{-1}. Finally, an active NE-trending extension is inferred also from focal mechanisms (Pondrelli *et al*., 2006) and borehole breakouts (Montone *et al*., 1999).

Recently, in 2002, a seismic sequence (mainshocks $M_w = 5.7$) struck eastern Molise. The seismic sequence occurred east of the Apennine chain with a deep focal depth (10-20 km) and right-lateral strike-slip kinematics on a E-W trending plane (Valensise *et al*., 2004; Chiarabba *et al*., 2005b; Di Luccio *et al*., 2005; Giuliani *et al*., 2007) suggesting a relation with the deformational activity due to the decoupling of the Adriatic region in a northern and a southern block (Westaway, 1990; Calais *et al*., 2002; D'Agostino, 2007).

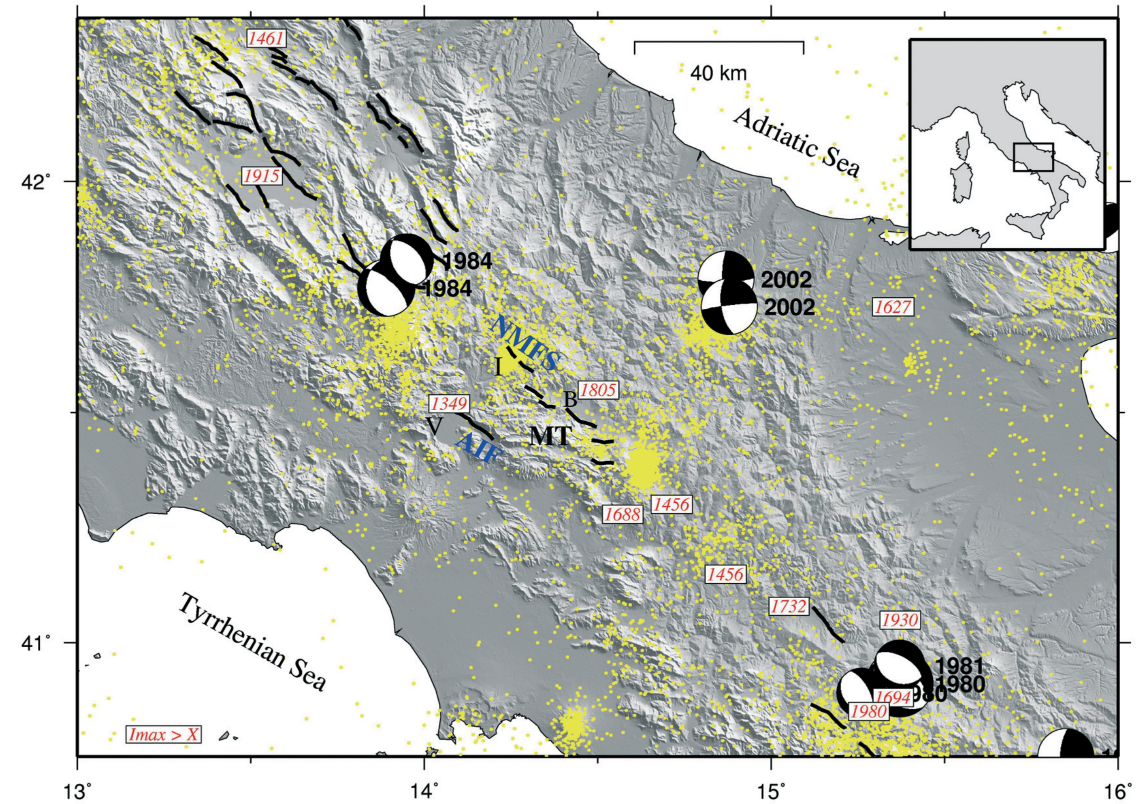

Fig. 1 - Seismotectonic map of the study area. Yellow dots are earthquakes from the instrumental INGV seismicity catalogue CSI (Castello *et al.,* 2006). Focal mechanisms are taken from the RCMT catalogue (Pondrelli *et al.,* 2006). Black lines are the trace of faults active during the Late Pleistocene-Holocene (Galli *et al.,* 2008a). Historical earthquakes with Imax > X are taken from the CPTI04 catalogue (Gruppo di Lavoro CPTI, 2004). B = Bojano basin, V = Venafro, MT = Matese Massif, AIF = Aquae Iuliae fault, NMFS = North-Matese fault system.

In the investigated area, the geological expression of the prevailing NE-SW extension, perpendicular to the axis of the chain, are Late Pleistocene faults. The northern Matese fault system (NMFS), bordering the Bojano-Isernia basins with a WNW-ESE trend, is a 30 km-long structure, one of the most studied active faults in the area (Guerrieri *et al.,* 1999; Blumetti *et al*., 2000; Galli and Galadini, 2003). According to Galli and Galadini (2003), this fault system was responsible for a 3rd BC event, beside the 1456 and 1805 ones [see also Blumetti *et al*. (2000)]. In Fig. 1, we plotted historical earthquakes from Gruppo di Lavoro CPTI (2004) coordinates, while, according to Camassi and Stucchi (1997), one of three main events of 1456 is localized near 1805 earthquake.

Along the SW edge of the Matese Massif, near Venafro, a NW-SE trending 20 km long fault has recently been associated to the 1349 earthquake by means of paleoseismological observations [Aquae Iuliae fault in Galli *et al*. (2008b)]. Two ancient high-energy earthquakes are also located in the same area the 346 (Galli *et al*., 2002) and 847 events (Figliuolo and Marturano, 2002). On the basis of the extension of the epicentral area of the 346 earthquake, it seems to be a multiple event similar to the 1456 large earthquake (Galadini and Galli, 2004).

3. GPS data

We have processed and combined permanent and non-permanent GPS data collected in the Molise and Campania regions. Survey-style GPS data were collected in a series of campaigns from 1994 to 2007. We measured the benchmarks of the IGM95 network (Surace, 1997), which is the first-order national geodetic GPS network first measured in 1994 by the IGM. This geodetic network covers the whole Italian territory with baselines between GPS sites of about 20 km. Thanks to IGM, we accessed the original data collected in 1994. The following GPS campaigns were carried out by the DPC, INGV and the APAT in 2001, 2003 and 2007. The selected IGM95 sub-network extends from the Tyrrhenian coast to the Adriatic coast, perpendicularly to the Apennine topographic axis and parallel to the regional direction of extension inferred from seismological, geodetic and geological data. This sub-network is made up of 20 vertexes from IGM95 plus a few other benchmarks [MS01, site monumentation made up by the APAT in 2001, and three more sites measured by INGV starting from 2001 in the epicentral area of the Molise 2002 earthquake: LESE, GUAR and CROC; Giuliani *et al*. (2007)]. Daily observations were collected in 8-24 hour repeated sessions. For the 1994 IGM measurements, we only considered sites for which repeated, daily sessions were available. The sessions for the 1994 measurements are generally of shorter duration (4-6 hours).

Rinex data, from available continuous sites, were collected from the ASI (http://geodaf.mt.asi.it), EUREF, IGS and Rete Integrata Nazionale GPS (RING) networks. The RING (http://ring.gm.ingv.it) is the GPS permanent network recently established by the INGV for the whole Italian territory. Code and phase data have been processed using the GIPSY-OASIS software from the NASA-Jet Propulsion Laboratory and related products (precise orbits, clocks and transformation parameters to International Terrestrial Reference Frame - ITRF2005). In a first step, we reduced the data using the Precise Point Positioning Strategy [PPP, Zumberge *et al*. (1997)] which processes undifferentiated data from single stations. Results from the PPP processing were brought together for ambiguity resolution including several IGS and EUREF sites to align the daily solutions to the ITRF2005 reference frame (Altamimi *et al*., 2007). Daily solutions and associated covariance matrices were then rotated in a reference frame realized by subtracting the rotation with respect to the ITRF2005 of 24 stations on the non-deforming part of the Eurasia plate. The Eurasia-ITRF2005 Eulerian pole parameters are listed in Table 1 with associated uncertainties.

We estimated the transformation for each day on the basis of selected common stations that are present both in the Eurasian-fixed solution and in the daily ambiguity network solutions. Final time series in a Eurasian reference frame locally rotated to NEU components were used to simultaneously solve, annual and semi-annual sinusoidal signals and antenna jumps for linear velocities. For non-permanent sites only a linear velocity was estimated from the time series.

To estimate velocity uncertainties we followed different approaches for permanent and non-permanent sites. The velocity uncertainties of permanent sites have been estimated with the software CATS (Williams, 2007) by taking into account both non-correlated (white noise) and temporally-correlated (flicker noise) site position effects. To avoid systematic biases associated with short observation intervals (Blewitt and Lavalleè, 2002), we only considered permanent sites with an observation interval longer than 2.4 years. To estimate the total uncertainty of survey site velocities σ, we add to the formal white noise uncertainty in velocity σ_{wn} an uncorrelated component

Table 1 - Parameters of the ITRF2005-Eurasia Eulerian pole. Smax and Smin are the semi-axes of the error ellipse, w is the rotation rate (°/my), Az is the azimuth of Smax, Sw is the 1-sigma rotation rate uncertainty. Also shown are the RMS of the residuals of horizontal velocities, the number of sites (Ns) used for the inversion and the normalized chi-squared (CHI^2/DOF).

Lat	Lon	w °/my	Smax	Smin	Az	Sw	RMS_E (mm/yr)	RMS_N (mm/yr)	Ns	CHI^2/DOF
-54.492	80.847	-0.257	0.7	0.2	-43.3	0.001	0.401	0.359	32	1.78
Sites used to define the Eurasia reference frame: ARTU,BOGO,BOR1,BRST,BRUS,CACE,CASC,CRAO,DRES,EBRE,GAIA,GLSV,HERS,JOZE,KARL,KOSG,LAMA,MDVO,MIKL,MLVL,MOBN,MOPI,MTPL,OBER, OBE2,POLV,POTS,PTBB,RIGA,TLSE,VILL,VLNS)										

of random walk noise σ_{rw} (Langbein and Johnson, 1997): $\sigma = \sqrt{\sigma_{wn}^2 + \sigma_{wn}^2}; \sigma_{wn} = a / \sqrt{(t)}$ where t is the time interval between the first and last survey in years and a is assumed to be 1 mm/yr$^{1/2}$.

In two cases, we have nearby permanent and non-permanent sites (RNI2-153X and TRIV-154X), separated by a few kilometres, which allows the comparison between permanent and non-permanent site velocities and associated uncertainties. In both cases, there is an excellent agreement between the two velocity estimates and the difference is largely contained within the respective error ellipses. This comparison provides confidence that velocity estimates are robust and uncertainties are correctly estimated.

We also included measurements from sites located in the epicentral area of the M_w 5.7 2002 Molise sequence (Di Luccio *et al*., 2005), the benchmarks of which have been used by Giuliani *et al.* (2007) to estimate the coseismic displacement and to infer fault geometry and slip of the faults. For these sites we only considered measurements taken after the 2002 earthquake. Site velocities in the Eurasian reference frames are listed in Table 2 together with their uncertainties, the observation time-span and the total number of observations.

4. GPS velocity field

The velocity field (Eurasia reference frame) for permanent and non-permanent sites is shown in Fig. 2. The main feature of the velocity field is shown by a clear divergence [see also D'Agostino and Selvaggi (2004) and Serpelloni *et al*. (2005)] between sites on the Tyrrhenian coast, moving NW at 1-2 mm/yr, and sites on the Adriatic side of the Apennines moving NE instead at 4-5 mm/yr. The overall effect of this divergence results in an active NE-SW extension across the Apennines, consistently with geological and seismological data. This one is the highest among the other values of extension rates measured across the Apennines obtained where dense networks of permanent and non-permanent sites are available [Northern Apennines 2-3 mm/yr: D'Agostino *et al*., 2009; Central Apennines 2-3 mm/yr: Mantenuto *et al*. (2007)]. The maximum extension from seismicity is interestingly corresponding to this sector of the Apennines (Selvaggi, 1998). This observation is consistent with the hypothesis of increasing extension rates induced by the clockwise rotation of Adria relative to Eurasia (Anderson and Jackson, 1987; Calais *et al*., 2002; Battaglia *et al*., 2004) along the Apennines. The velocity field also shows that the largest velocity gradient matches documented active faults and large historical earthquakes.

Table 2 - GPS velocities in the Eurasia reference frame. East and north horizontal velocities, Ve and Vn, and associated 1-sigma uncertainties Se and Sn are expressed in mm/yr. Corr is the correlation coefficient between Se and Sn. Dt is the observation interval and Nobs the total number of observations.

Lon	Lat	Ve	Vn	Se	Sn	Corr	STA	Dt	Nobs
CGPS:									
8.763	41.928	0.28	0.18	0.12	0.09	0.05	AJAC	7.10	1838
4.359	50.798	-0.50	0.01	0.17	0.12	0.06	BRUS	7.10	2330
14.594	41.546	0.57	2.87	0.43	0.29	0.24	BSSO	3.06	934
8.973	39.136	0.42	0.15	0.23	0.15	0.01	CAGL	7.10	2103
0.492	40.821	0.46	-0.36	0.12	0.12	0.10	EBRE	7.10	2085
10.211	42.753	-0.31	0.51	0.15	0.10	-0.10	ELBA	7.10	2195
8.921	44.419	0.36	-0.12	0.13	0.12	-0.03	GENO	7.10	2211
30.497	50.364	-0.55	0.21	0.23	0.16	0.15	GLSV	6.87	2234
6.921	43.755	-0.17	0.48	0.16	0.18	0.05	GRAS	7.10	2157
15.493	47.067	0.70	0.47	0.17	0.13	0.02	GRAZ	7.10	2167
15.060	41.073	0.51	2.29	0.32	0.21	0.14	GROT	3.71	1150
21.032	52.097	-0.57	0.00	0.20	0.21	0.10	JOZE	7.10	2276
12.606	35.500	-2.77	3.07	0.21	0.12	0.12	LAMP	7.10	2135
0.155	48.019	0.04	0.20	0.21	0.17	0.07	MANS	7.05	2161
16.704	40.649	1.07	4.04	0.16	0.11	0.04	MATE	7.10	2318
14.990	36.876	-1.50	4.72	0.26	0.13	0.02	NOT1	7.09	2268
18.680	45.561	0.73	0.63	0.22	0.13	0.01	OSJE	7.10	1683
11.896	45.411	0.23	1.19	0.12	0.17	-0.03	PADO	6.19	1661
13.066	52.379	-0.26	-0.09	0.11	0.08	0.03	POTS	7.10	2279
353.146	33.998	-3.33	1.27	0.33	0.22	0.09	RABT	7.06	2266
14.152	41.703	-0.04	3.03	0.34	0.20	-0.04	RNI2	3.49	1098
15.209	40.925	0.42	2.43	0.37	0.28	0.06	SNAL	3.46	1090
7.661	45.063	0.42	0.02	0.14	0.14	-0.05	TORI	7.10	2311
14.550	41.767	1.10	3.45	0.49	0.27	0.18	TRIV	3.36	922
11.878	45.407	1.49	1.59	0.94	1.09	-0.01	UPAD	0.89	212
356.048	40.444	0.39	0.65	0.20	0.12	0.00	VILL	7.10	2179
12.879	49.144	-0.09	0.50	0.18	0.12	0.04	WTZR	7.09	1984
356.911	40.525	-0.08	-0.24	0.17	0.11	0.03	YEBE	7.10	2256
7.465	46.877	0.02	0.38	0.13	0.08	-0.04	ZIMM	7.10	2135
13.124	43.112	1.50	3.17	0.19	0.17	0.15	CAME	7.10	1619
12.493	41.893	-0.18	1.38	0.20	0.16	0.16	M0SE	5.98	1751
16.704	40.649	1.31	3.67	0.18	0.14	-0.01	MAT1	6.58	2008
15.651	38.108	1.12	3.52	0.22	0.14	-0.06	TGRC	6.69	1814
15.266	40.231	0.26	2.00	0.33	0.28	-0.08	VLUC	7.10	1637
15.724	40.601	0.41	4.35	0.24	0.12	0.02	TITO	6.99	1675
13.350	42.368	0.38	2.19	0.19	0.15	0.60	AQUI	7.10	2197
14.669	41.974	1.26	3.64	0.51	0.37	0.14	FRES	2.39	684
14.050	40.876	-2.44	2.14	0.30	0.17	0.03	LICO	4.10	1192
Surveys:									
14.389	41.933	0.70	2.08	0.48	0.48	0.05	1531	6.00	11
14.306	41.788	2.59	3.46	0.43	0.43	0.09	1532	12.94	12
14.139	41.712	-0.08	2.50	0.54	0.54	-0.03	153X	12.90	11
14.815	41.922	2.35	4.48	0.47	0.47	0.11	1541	12.79	14
14.737	41.760	1.73	3.26	0.69	0.69	-0.08	1542	4.55	8
14.534	41.965	2.59	2.88	0.62	0.62	-0.01	1543	6.04	9
14.552	41.782	1.49	4.01	0.80	0.80	0.23	154X	8.71	11
13.937	41.542	0.72	2.82	0.43	0.43	-0.01	1601	12.93	11
13.891	41.404	-1.52	0.93	0.72	0.72	0.00	1602	12.88	10
14.326	41.587	0.30	3.44	0.49	0.49	0.05	1611	12.90	22
14.399	41.465	1.23	2.85	0.50	0.50	0.03	1612	12.92	15
14.033	41.438	-0.67	3.73	0.61	0.61	0.00	1613	6.08	9
14.127	41.579	0.44	2.48	0.41	0.41	0.01	1614	12.94	10
14.832	41.695	0.41	4.35	0.62	0.62	0.03	CGUA	5.03	8
14.944	41.668	0.38	3.01	0.52	0.52	0.00	CROC	5.03	7
14.800	41.709	2.28	4.13	0.49	0.49	0.00	LESE	5.04	7
13.858	41.143	-2.44	1.51	0.56	0.56	0.06	MS01	6.04	9

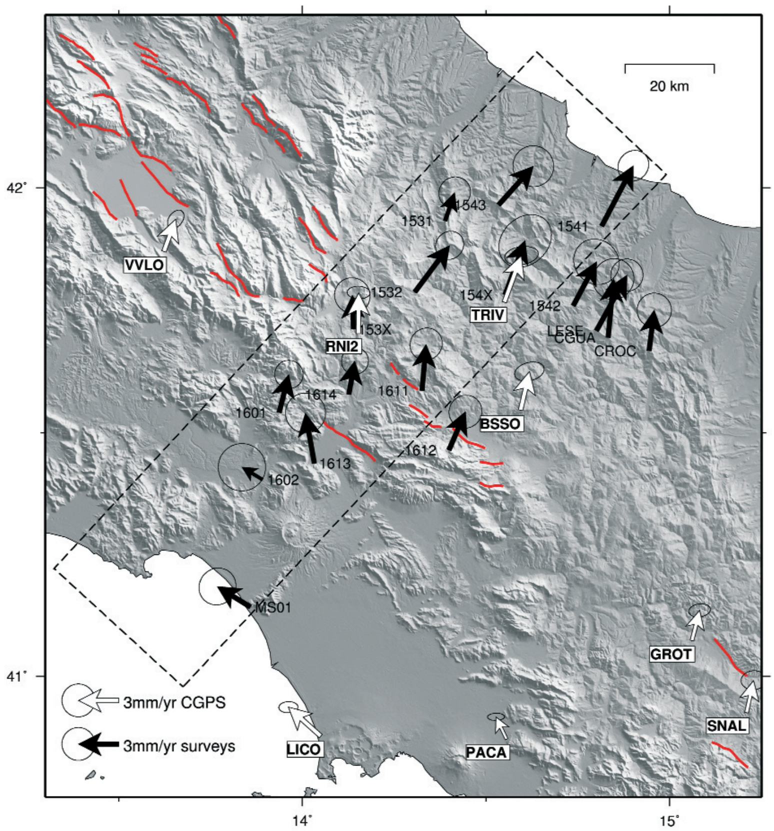

Fig. 2 - Velocity field of permanent (white arrows) and non-permanent (black arrows) GPS sites with associated 95% CI error ellipses. The dashed line box includes the GPS sites used to project velocities along the trace of the profile of Fig. 3.

In particular, we observe two high gradients (Figs. 1 and 2): one in the supposed epicentral area of the 1349 earthquake in the middle Volturno Valley (close to the village of Venafro) and a second significant gradient, NE of the Isernia basin, between the permanent sites RNI2 and TRIV, close to the mesoseismic area of both the 1805 and the 1456 earthquakes, associated to the North-Matese fault system [Bojano- Isernia Basins; Galli and Galadini (2003); Figs. 1 and 2]. Because of the reduced number of sites, SW of the Matese mountains (few benchmarks were vandalized and lost), the estimate of the extension across the Bojano basin is uncertain. Crossing the drainage divide, velocity gradients appear to be less dramatic as they correspond to lower deformation rates; with the exception of the area of the 2002 earthquake where some significant differential motion of the sites located across the surface projection of the 2002 earthquake fault has been observed. This is consistent with continuing right-lateral strain accumulation. These results, at the moment, are to be interpreted with caution as the velocities of these sites have been determined from data obtained in only 2 post-earthquake campaign measurements.

In order to facilitate the evaluation of strain accumulation on the active faults documented in the area, we plot the velocity component parallel to a profile across the Apennines (Fig. 3). We narrowed the width of the swath used to project site velocities along the trace of the profile to the north-western part of our network, where site distribution is continuous from the Tyrrhenian to the Adriatic coast.

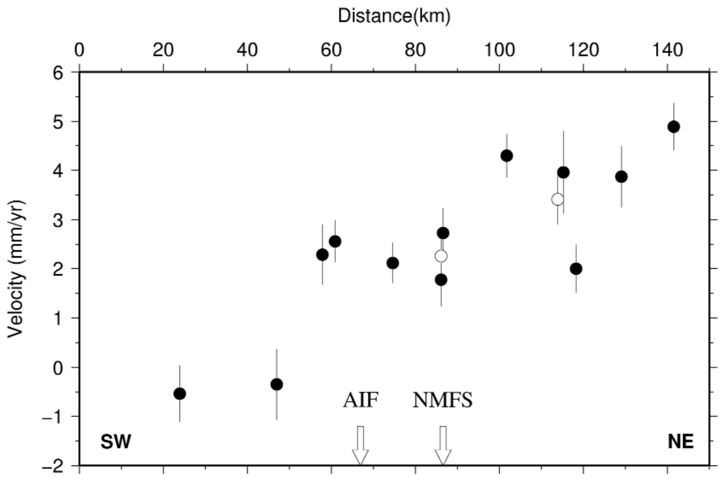

Fig. 3 - Plots of permanent (white circles) and non-permanent (black dots) GPS velocities projected along the trace of the profile shown in Fig. 2. The arrows on the bottom point to the location of the Aquae Iuliae fault (AIF) and of the North-Matese fault system (NMFS).

Fig. 3 shows that the overall 4-5 mm/yr extension across the Apennines presents two major gradients in the Venafro area and in the Isernia basin. The first gradient matches with Aquae Iulie fault, recently associated with one of the main shocks that in 1349 devastated central and southern Italy (Galli *et al*., 2008b). The second gradient is observed NE of Isernia where previous works have documented the opening of superficial breaks along SW-dipping faults of the southern slope of the Samnium hills in relation to the 1805 earthquake [North-Matese fault system; Galli and Galadini (2003)]. Therefore, we suggest that strain accumulation can be currently divided distributed these two fault systems (Aquae Iulie fault and North-Matese fault system).

5. Strain rates

The evaluation of the deformation regime and its rate can be estimated by calculating the strain rate tensor within polygons where the deformation regime is considered homogeneous. Fig. 4 shows the strain rate tensors calculated for three different polygons, the vertexes of which are defined by GPS sites. The strain rate tensor is calculated considering site velocities located at the boundaries and within the polygons and estimating velocity gradients by using a standard weighted least-squares approach. Polygons have been defined considering the GPS site distribution and the distribution of known active faults. Due to the limited number of measurements, we exclude the sites located close to the 2002 earthquake sequence.

The principal axes of the strain rate tensor (Fig. 4) point to a NE-SW extension across the Apennines as shown also from the focal mechanisms and from the fault geometry and the kinematics inferred from geological and paleoseismological data. As already noticed on the basis of the observation of the velocity field, it is possible to define two different behaviours: a highest value of strain for the western sector around Venafro of 64 ± 24 nanostrain/yr (Fig. 4) and a lower value of extension for the sector immediately NE of 42 ± 12 nanostrain/yr. A marginally significant NW-SE contraction of 26 ± 18 nanostrain/yr is found on in the Adriatic side of the

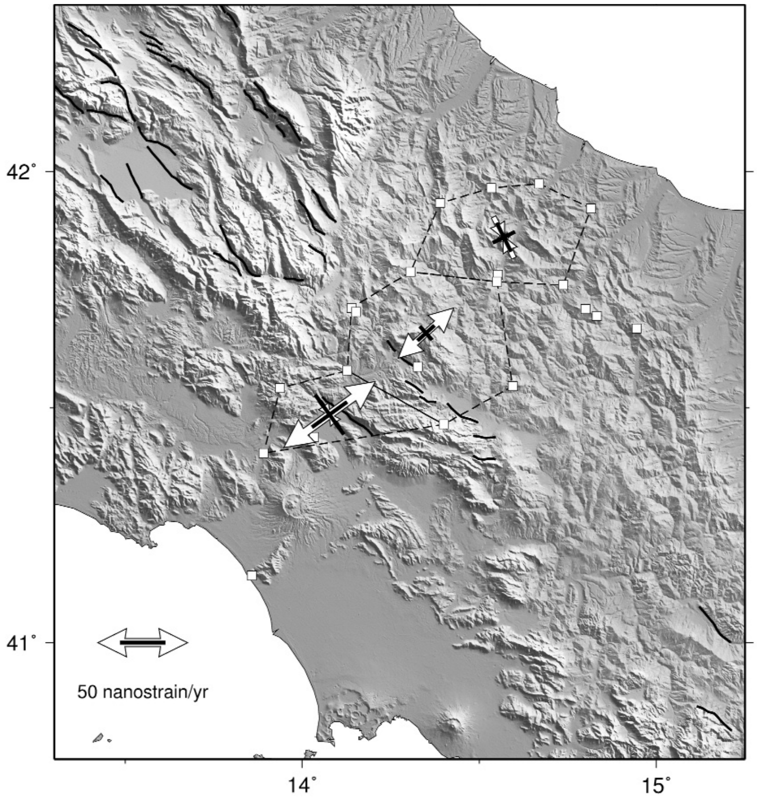

Fig. 4 - Principal axes of the horizontal strain rate tensor and associated 1-sigma uncertainty for the polygons defined by the black dashed lines. The white squares are the GPS sites used.

Apennines. These results suggest that significant strain accumulation is active along the axial belt of the Apennines, being characterized by uni-axial NE-SW extension; this process is consistent with accumulation of strain potentially released by normal faulting on NW-SE oriented faults. Strain accumulation on the Adriatic side of the Apennines is marginally consistent with contraction and strain accumulation on E-W oriented strike slip faults. More measurements are needed to put firmer constraints on strain accumulation in this area.

6. Conclusion

We present the velocity and strain field derived from the analysis of more than 20 sites (a sub-network of the IGM95 first-order national GPS network), with a dense distribution, measured during a series of GPS campaigns from 2001 to 2007, with several repetitions on each vertex, combined with data of GPS permanent stations (INGV - RING network). Considering that the processing included original IGM observations of 1994, the velocities are calculated over a 13 years time span.

The geodetic velocity field and derived strain rates, even if obtained from a rather short time span of 13 years, are coherent with geologic data on the active deformation of the area and with seismicity information. This paper is mostly based on survey-style GPS results, using a very dense network giving a high-resolution image of an active deformation distribution. Moreover, the excellent agreement between the survey-style results and permanent station results is a confirmation of the quality of the presented results.

The total amount of extension accommodated from the Tyrrhenian to the Adriatic coast in this sector of the southern Apennines is 4-5 mm/yr, which represents the maximum value measured in the Apennines.

The velocity field shows two main gradients in the velocity values resulting in an active extension located in the mesoseismic area of the largest historical earthquakes, and matching surface faulting evidence. In fact, according to the strain distribution, the total amount of extension is localized in two distinct sectors of Apennines where, the deformation is accommodated by two fault systems that, on the basis of geological and paleoseismological observations, are associated with the largest earthquakes of the area (i.e., 346, 847, 1349, 1456, 1805 events).

REFERENCES

Altamimi Z., Collilieux X., Legrand J., Garayt B. and Boucher C.; 2007: *ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters.* J. Geophys. Res., **112**, B09401, doi:10.1029/2007JB004949.

Anderson H. and Jackson J.; 1987: *Active tectonics of the Adriatic region.* Geophys. J. R. Astron. Soc., **91**, 937–983.

Battaglia M., Murray M.H., Serpelloni E. and Burgman R.; 2004: *The Adriatic region: independent microplate within the Africa - Eurasia collision zone*. Geophys. Res. Lett., **31**, L09605, doi:10.1029/ 2004GL019723.

Blewitt G. and Lavallée D.; 2002: *Effect of annual signals on geodetic velocity*. J. Geophys. Res., **107** (B7), 342 doi:10.1029/2001JB000570.

Blumetti A.M., Caciagli M., Di Bucci D., Guerrieri L., Michetti A.M. and Naso G.; 2000: *Evidenze di fagliazione superficiale olocenica nel bacino di Bojano (Molise)*. In: 19° Convegno Nazionale GNGTS, Riassunti estesi delle Communicazioni, Esagrafica, Roma, pp. 12–15.

Calais E., Nocquet J.M., Jouanne F. and Tardy M.; 2002: *Current strain regime in the western Alps from continuous Global Positioning System measurements, 1996–2001*. Geology, **7**, 651–654.

Camassi R. and Stucchi M.; 1997: *Catalogo parametrico dei terremoti italiani al di sopra della soglia di danno.* C.N.R. GNDT, Milano, 96 pp.

Castello B., Selvaggi G., Chiarabba C. and Amato A.; 2006: *CSI Catalogo della sismicità italiana 1981-2002.* Versione 1.1. INGV-CNT, Roma, http://www.ingv.it/CSI/.

Chiarabba C., Jovane L. and Di Stefano R.; 2005a: *A new view of Italian seismicity using 20 years of instrumental recordings.* Tectonophysics, **395**, 251–268.

Chiarabba C., De Gori P., Chiaraluce L., Bordoni P., Cattaneo M., De Martin M., Frepoli A., Michelini A., Monachesi A., Moretti M., Augliera G.P., D'Alema E., Frapiccini M., Gassi A., Marzorati S., Di Bartolomeo P., Gentile S., Govoni A., Lovisa L., Romanelli M., Ferretti G., Pasta M., Spallarossa D. and Zunino E.; 2005b; *Mainshocks and aftershocks of the 2002 Molise seismic sequence, southern Italy.* J. Seismol., **9**, 487–494.

D'Agostino N.; 2007: *Present-day microplates motion in the central Mediterranean.* Eos Trans. AGU, **88** (52), Fall Meet. Suppl., Abstract G21C - 0658.

D'Agostino N. and Selvaggi G.; 2004: *Crustal motion along the Eurasia-Nubia plate boundary in the Calabrian Arc and Sicily and active extension in the Messina Straits from GPS measurements.* Journal Gephysical Research, **109**, B11402, doi: 10.1029/ 2004JB002998.

D'Agostino N., Giuliani N.R., Mattone M. and Bonci L.; 2001: *Active crustal extension in the Central Apennines (Italy) Inferred from GPS measurements in the interval 1994-1999*. Geophys. Res. Lett., **28**(10), 2121-2124.

D'Agostino N., Cheloni D., Mantenuto S., Selvaggi G., Michelini A. and Zuliani D.; 2005: *Strain accumulation in the* *southern Alps (NE Italy) and deformation at the northeastern boundary of Adria observed by CGPS measurements.* Geophys. Res. Lett., **32**, L19306, doi:10.1029/2005GL024266.

D'Agostino N., Mantenuto N.S., D'Anastasio E., Avallone A., Barchi M., Collettini C., Radicioni F., Stoppini A. and Fastellini G.; 2009: *Contemporary crustal extension in the Umbria-Marche Apennines from regional CGPS networks and comparison between geodetic and seismic deformation.* Tectonophysics, submitted.

Di Luccio F., Fukuyama E. and Pino N.A.; 2005: *The 2002 Molise earthquake sequence: what can we learn about the tectonics of southern Italy?* Tectonophysics, **405** (1–4), 141–154.

Figliuolo B. and Marturano A.; 2002: *Terremoti in Italia meridionale dal IX all'XI secolo.* In: Marturano A. (a cura di), Contributi per la storia dei terremoti nel bacino del Mediterraneo, Laveglia Editore, pp. 33-52.

Galadini F. and Galli P.; 2004: *The 346 A.D. earthquake (Central-Southern Italy): an archaeoseismological approach.* Annals of Geophysics, **47**, 885-905.

Galli P. and Galadini F.; 2003: *Disruptive earthquakes revealed by faulted archaeological relics in Samnium (Molise, southern Italy).* Geophys. Res. Lett., **30** (5), 1266, doi: 10.1029/2002GLO16456.

Galli P., Galadini F. and Carpini S.; 2002: *Analisi archeosismologiche nel santuario di Ercole di Campochiaro (Matese). Evidenze di un terremoto distruttivo sconosciuto e implicazioni sismotettoniche.* Il Quaternario, **15** (2), 155-167.

Galli P., Galadini F. and Pantosti D.; 2008a: *Twenty years of paleoseismology in Italy.* Earth-Science Reviews, **88**, 89-117.

Galli P., Naso G., Piscitelli S., Giocoli A., Hailemikael S. and Rizzo E.; 2008b: *Unmasking the 1349 earthquake fault: paleoseismological indications from the Latium-Campania border (central Italy).* Geophysical Research Abstracts, **10**, EGU General Assembly 2008.

Giuliani R., Anzidei M., Bonci L., Calcaterra S., D'Agostino N., Mattone M., Pietrantonio G., Riguzzi F. and Selvaggi G.; 2007: *Co-seismic displacements associated to the Molise (Southern Italy) earthquake sequence of October – November 2002 inferred from GPS measurements.* Tectonophysics, **432**, 21-35.

Gruppo di Lavoro CPTI; 2004; *Catalogo Parametrico dei Terremoti Italiani, versione 2004.* INGV, Bologna, http://emidius.mi.ingv.it/CPTI04.

Guerrieri L., Scarascia G. and Vittori E.; 1999: *Analisi stratigrafica e geomorfologica della conoide tardo-quaternaria di Campochiaro ed implicazioni per la conca di Bojano in Molise.* Il Quaternario, **12**, 237–247.

Hunstad I., Selvaggi G., D'Agostino N., England P., Clarke P. and Pierozzi M.; 2003: *Geodetic strain in peninsular Italy between 1875 and 2001.* Geophys. Res. Lett., **30**(4), 1181, doi:10.1029/2002GL016447, 388 2003.

Langbein J. and Johnson H.; 1997: *Correlated errors in geodetic time series: Implications for time-dependent deformation.* J. Geophys. Res., **102**(B1), 591– 604.

Mantenuto S., Bonci L., Calcaterra S., D'Agostino N., Giuliani R., Mattone M. and Merli K.; 2007: *Analysis of active extension in the Central Apennines (Abruzzo, Italy) using GPS measurements.* In: EGU General assembly, Wien 15–20 April. Geophysical Research Abstracts 9, 04341.

Montone P., Amato A. and Pondrelli S.; 1999: *Active stress map of Italy.* J. Geophys. Res., **104**, 25595–25610.

Patacca E. and Scandone P.; 1989: *Post-Tortonian mountain building in the Apennines: the role of the passive sinking of a relic lithospheric slab*. In: Boriani A., Bonafede M., Piccardo G.B. and Vai G.B. (eds), The Lithosphere in Italy: Advance in Earth Science Research, Accademia Nazionale dei Lincei, Rome, pp. 157–176.

Pondrelli S., Salimbeni S., Ekström G., Morelli A., Gasperini P. and Vannucci G.; 2006: *The Italian CMT dataset from 1977 to the present.* Phys. Earth Planet. Int., **159**/286- 303.

Selvaggi G.; 1998: *Spatial distribution of horizontal seismic strain in the Apennines from historical earthquakes*. Ann. Geof., **41**(2), 241-251.

Serpelloni E., Anzidei M., Baldi P., Casula G. and Galvani A.; 2005: *Crustal velocity and strain-rate fields in Italy and surrounding regions: New results from the analysis of permanent and non-permanent GPS networks*. Geophys. J. Int., **161**, 861–880, doi:10.1111/j.1365-246X.2006.06218.x.

Surace L.; 1997: *La nuova rete geodetica nazionale IGM95: risultati e prospettive di utilizzazione.* Boll. Geod. Sci. Affini, **3**, 358–378.

Valensise G., Pantosti D. and Basili R.; 2004: *Seismology and tectonic setting of the Molise earthquake sequence of October 31– November 1, 2002.* Earthq. Spectra, **20** (S1), S23–S37.

Westaway R.; 1990: *Present-day kinematics of the plate boundary zone between Africa and Europe, from the Azores to the Aegean.* Earth Planet. Sci. Lett., **96**, 393–406.

Williams S.D.P.; 2007: *CATS: GPS coordinate time series analysis software.* GPS solut., DOI 10.1007/s10291- 007-0086-4.

Zumberge J.F., Heflin M.B., Jefferson D.C., Watkins M.M. and Webb F.H.; 1997: *Precise point positioning for the efficient and robust analysis of GPS data from large networks,* J. Geophys. Res., **102**, 5005-5017.

Corresponding author: Roberta Giuliani
Dipartimento della Protezione Civile
Ufficio Rischio Sismico - SAPE
Via Vitorchiano 4, 00189 Roma (Italy)
phone: +39 06 68204106; fax: +39 06 68202877; e-mail: roberta.giuliani@protezionecivile.it